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Theory of photoacoustic effect in media with thermal memory

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This paper presents a model for indirect photoacoustic response that includes thermal memory effects. At low frequencies, the model reduces to the well-known thermal piston model of photoacoustic response given by Rosencweig and Gersho. However, at high frequencies, the presented model predicts resonant behavior of amplitudes and phases of photoacoustic response and determines the respective resonant frequencies. The results of the presented model enable experimental determination of standard thermal properties of solids (thermal diffusivity and thermal conductivity), as well as thermal memory properties, thermal relaxation time, and heat propagation speed. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4885458>]

I. INTRODUCTION

The photoacoustic (PA) effect represents acoustic emission due to the light absorption and subsequent heat generation.¹ It belongs to quite wide family of related phenomena, commonly called photothermal (PT) phenomena, which are caused by heat generation due to the light absorption.^{1–10} Their potentials as tool for non-destructive material characterization and evaluation^{4–8} lead to extensive studies of the PT phenomena during the last three decades.

The PA effect was discovered in 1880 by Alexander Graham Bell during his research of means for wireless communication (photophone).^{9,10} In 1976, Rosencweig and Gersho explained the basic physical mechanisms governing the PA effect in solids through development of a quantitative theoretical model (known as the RG model, or the thermal piston model) which related physical properties of the irradiated sample to the measured acoustic signal.¹ The RG model enabled application of the PA effect for investigations of material properties. Ever since its foundation, RG model was the basis for many extensions and further applications, and the research efforts followed two basic directions.

The first direction of development of RG model is further study of the physical processes that contribute to the PA effect. Namely, the RG model is based on assumption that the main contribution to the PA effect is the heat flow from the irradiated sample to the adjacent gas. By inclusion of other influences on the PA response, like thermo-mechanical vibrations of surface of the sample and finite dimensions of the gas column in PA cell, Bennett and Forman,¹¹ Wetsel and McDonald,¹² Aamodt *et al.*,¹³ McDonald and Wetsel,¹⁴ McDonald,² Roussette *et al.*,¹⁵ and other investigators^{4,16,17} developed several more complex models that enabled application of PA effect in various experimental setups, such as open-ended PA cells, resonant PA cells, detection of direct PA effect, and others.⁴ However, it was experimentally confirmed that the RG model describes sufficiently well PA

response in almost all investigated cases of standard reflective PA cell setup and gas-microphone detection.^{4,18}

The second direction of development of the RG model represents various generalizations of RG model with the aim to describe influences that are specific for certain categories of the samples, as it is the case with optically generated plasma waves in semiconductors,^{19–22} gas diffusion in porous samples,^{23,24} continuously heterogeneous structure of the irradiated samples,^{25–27} multilayered samples,^{18,28–37} and other. Each of the generalizations of the RG model provided further possibilities for application of the PA effect for material characterization by measurements of electronic properties, porosity, profile of non-homogeneity, and related physical properties.

Diversity of the mentioned models enabled application of PA methods in various areas of science and engineering,³⁸ and motivated further development and application of PA measurement techniques. However, almost all of the models for PA and PT phenomena, with very few exceptions,^{28,29,39–43} are based on Fourier's classic heat conduction theory.⁴⁴ It is well-known that the theory implicitly adopts infinite speed of propagation of heat, which is not acceptable from fundamental theoretical point of view. There are several available generalized heat conduction theories^{45–50} that corrected this drawback of the classical heat conduction theory on various theoretical bases, from microscopic approach^{46,47} to extended irreversible thermodynamics⁴⁹ and harmonization of heat conduction theory with general relations of mechanics of continuum.⁴⁸ The common result of all the theories and approaches is that in linear approximation, the heat conduction process is described by a hyperbolic differential equation.^{41,48} Besides thermal conductivity and thermal diffusivity as thermal properties of matter used in classic theory, the hyperbolic differential equation also contains the finite heat propagation speed and the respective non-zero thermal relaxation time as inherent properties of matter that affect time-dependent heat conduction processes.

So far, experimental procedure for measurements of thermal propagation speed and thermal relaxation times are not proposed. Theoretical predictions of thermal relaxation

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